Appendix B—Byron Site Data

The Byron site has been the subject of a series of environmental investigations from 1974 through 1993, with the collection of data for routine monitoring continuing to the present (2002). The investigations that form the primary basis for this discussion were conducted from 1987 through 1993 and are presented in Kay and others, 1989; U.S. Environmental Protection Agency, 1994; Kay and others, 1997; and Kay and others, 1999. These reports provide a detailed discussion of the methods used for, and results of, the hydrogeologic investigations at the Byron site performed by the USGS and USEPA. A total of 26 investigative methods were used to develop the hydrogeologic framework for the Byron site (table 3).

Previous Studies

Sargent and Lundy, Inc., and Dames and Moore, Inc. (1975) investigated fracture orientations in the Galena-Platteville dolomite in and around the Byron site. The investigation identified two primary directions of strike of the vertical fractures: N. 60° W. to N. 75° W. and N. 15° E. to N. 30° E. The trend from N. 60° W. to N. 75° W. is the dominant structural trend. The investigation also identified a fault in the Galena-Platteville dolomite south of the Byron site. Part of the fault is outlined by the topographic low associated with Woodland Creek (fig. 6). The fault has a measured maximum vertical displacement of 6 in. and is oriented N. 60° W. Faulting and fracture development was attributed to movement along the Sandwich Fault zone.

Topographic and Aerial Photographic Analysis

Analysis of land-surface topography during site visits, topographic maps, and aerial photographs defined a prominent bedrock ridge associated with the topographic upland as well as the presence of various depressions potentially associated with fracture traces at the Byron site (U.S. Environmental Protection Agency, 1994) (figs. 6, 7) (table 2). The most prominent fracture trace is associated with the potential fault defined by Woodland Creek. Additional fracture traces also were identified at the BSY and the DFP. The fracture traces tend to be oriented approximately parallel to the dominant vertical fracture orientation at about N. 60° W. (Woodland Creek and the Northwest Ravine), orthogonal to the dominant vertical fracture orientation at N. 30° E. (West Ravine and Northeast Ravine), or approximately due north.

Two circular depressions about 60 ft across were identified near the BH14 well cluster and approximately halfway between wells MW3 and DF15 (fig. 6) during site visits. These circular depressions are interpreted as being sinkhole locations.

Quarry Visits

The Galena-Platteville dolomite at the Benesh Quarry and the quarries near Meyer's Spring (fig. 6) is composed of generally massive dolomite with a network of vertical and horizontal fractures. The orientation of the vertical fractures in the quarry near Meyer's Spring was measured and found to be consistent with the fracture orientations reported by Sargent and Lundy and Dames and Moore, Inc., (1975).

Collapse features 10-15 ft wide were observed in the dolomite deposits at the Benesh Quarry. The collapse features appear to have been formed by the dissolution of dolomite in the upper part of the Grand Detour Formation (Dennis Kolata, Illinois State Geological Survey, oral commun., 1994). Collapse features do not appear to extend to the overlying deposits, indicating that the Grand Detour Formation may have greater secondary permeability than the other formations in the Platteville and Galena Groups at this site.

Surface Geophysics

GPR surveys were conducted in 1988 and 1991 at various locations in the upland part of the Byron site to determine if buried objects were present. A secondary objective of the GPR surveys was to identify fractures and sinkholes. The high clay content in the soil limited the depth of penetration of the GPR signal to approximately 5 ft, which is less than the depth to bedrock. A radio transmission tower in the area also was a source of signal interference during the GPR surveys. Therefore, surface GPR was not of use in the characterization of the Galena-Platteville dolomite at the Byron site.

An azimuthal square-array resistivity survey was conducted on the northeastern part of the DFP to determine the orientation of fractures in the dolomite. The results from this survey did not indicate a preferred fracture orientation. It is possible that the survey lines were too short to obtain measurements that penetrated the overburden and measured properties of the bedrock. The use of resistivity was not investigated further at the Byron site.

Lithologic Logs

Lithologic logs were prepared for all of the wells drilled during environmental investigations at the Byron site (table 3). Lithologic logs indicate that the Galena-Platteville deposits in the upland areas tend to be primarily competent dolomite yielding small amounts of water interspersed with small hydraulically productive zones indicative of fractures and vugs. Softer, more hydraulically productive dolomite was identified beneath much of the West Ravine. Loss of cuttings and formation water near the bottom of wells DF12, DF24, B6R, at the AW4 well cluster (fig. 7), and at an abandoned well between wells MW39 and DF12 indicated the presence of high-permeability fractures or solution openings at these locations (tables 5, 6). Cuttings returned during drilling of well DF14 contained large amounts of silt and clay and little water, indicating infilling of the sinkhole in this area.

Core Analysis

Cores collected at wells MW2, MW20, DF4D, AW1D, AW4S, and AW4D were described and analyzed for stratigraphy (Michael Sargent, Illinois State Geological Survey, written commun., 1992). The Pecatonica, Mifflin, Grand Detour, Nachusa, Quimbys Mill, Guttenberg, and Dunleith Formations were identified from the cores (fig. 11). The Galena-Platteville deposits primarily are dolomite with variable amounts of limestone. The Guttenberg Formation was identified as approximately 5 ft thick at wells MW2 and AW1D, but was about 0.5 ft thick at well MW20.

Vertical fractures, many of which were healed or infilled with clay minerals, and vuggy intervals were identified throughout the Galena-Platteville deposits underlying the site. Although fractures were identified throughout each of the cores, fractured and weathered zones indicative of permeable features were identified in the cores at about 795 and 773 FANGVD29 in well AW1D, at about 750 FANGVD29 in well AW4S, at 736-742 FANGVD29 in well DF4D, and at about 691-703 FANGVD29 in well MW20.

The porosity of the Galena-Platteville deposits determined from analysis of 79 rock samples collected from the cores ranged from about 4 to 22 percent with a median value of about 10 percent (Patrick Mills, U.S. Geological Survey, written commun., 1993). The median porosity value was 6.4 percent for the Guttenberg Formation (fig.11), ranged from 9 to 10.3 percent for the Pecatonica, Mifflin, Nachusa, Quimbys Mill and Dunleith Formations, and was 11.3 percent for the Grand Detour Formation.

Geophysical Logs

Geophysical logging was invaluable in expanding the geologic framework of the Byron site and providing foundation for the hydraulic framework (table 3).

Borehole Camera

Borehole camera logs were run in 11 wells and boreholes, primarily located on or near the Salvage Yard (table 3). Results of camera logging were not discussed in the previous reports on the site, and, therefore, are discussed in greater detail in this report than many of the other logging methods.

Camera logging in borehole PZ1 indicated generally competent rock throughout the borehole. Small fractures were indicated above the water surface at about 767, 800, 808, 809, and 812 FANGVD29 and below the water surface at about 749 and 734 FANGVD29 (table 5). Various large fractures were identified at 708-712 FANGVD29. Water was observed cascading down the sides of the borehole from about 793 ft to the water surface at 761 FANGVD29.

Camera logging in borehole PZ2 indicated generally competent rock throughout the borehole. Small fractures were indicated above the water surface at 806-814 FANGVD29 and below the water surface at about 794 and 790 FANGVD29. Heavy iron flocculate in the water below 763 FANGVD29 obscured clear identification of features, but various possible fractures were identified from 684 to 696 FANGVD29. Water was observed cascading down the sides of the borehole from about 798 FANGVD29 to the water surface at 794 FANGVD29.

Camera logging in borehole PZ3 indicated generally competent rock throughout the borehole. Subhorizontal planar features were identified at 739-741 and 753-756 FANGVD29. Small fractures were observed at about 747 and 749 FANGVD29. Heavy iron flocculate in the water column and algae on the sides of the borehole prevented identification of features below about 725 FANGVD29, with the exception of a possible fracture at about 698 FANGVD29. Water was observed cascading down the sides of the borehole from about 794 FANGVD29 to the water surface.

Cascading water observed above the water surface in the PZ boreholes appeared to drain from the aquifer matrix and was not associated with identifiable secondary-permeability features. Cascading water indicates that the water table is more than 10 ft above the water surface in the PZ boreholes.

Camera logging in borehole SPW indicated numerous vuggy intervals and fractures over most of the borehole (table 5). Vertical fractures were identified above the water surface at about 765 FANGVD29, and below the water surface between about 736 and 751

FANGVD29, and about 710-718 FANGVD29. A series of horizontal planar features were identified at about 724 FANGVD29 and at 695-700 FANGVD29. Water was observed dripping from the sides of the borehole from about 794 FANGVD29 down to the water surface.

Camera logging in borehole DF4D indicated generally competent rock throughout the borehole. Fractures were identified at about 723 and 748 FANGVD29 (table 5). Camera logging in this borehole was terminated at about 718 FANGVD29, above the bottom of the borehole. Camera logging in borehole DF5S indicated competent rock throughout the borehole.

Camera logging in borehole DF15 indicated generally competent rock. Numerous subhorizontal fractures were identified between 747 and 754 FANGVD29, and at about 761 FANGVD29.

Camera logging in borehole DF17 indicated numerous fractures over the length of the borehole (table 5). Fractures especially were concentrated at 714-720, 754-759, and 790-805 FANGVD29. A large solution opening was recorded near the bottom of the borehole at about 694-700 FANGVD29.

Camera logging in borehole DF12 indicated numerous vugs, fractures, and solution openings throughout the length of the borehole (table 5). Fractures and solution openings were observed from about 729 FANGVD29 to the bottom of the borehole at 702 FANGVD29, with a cavern identified at 702 FANGVD29.

Camera logging in boreholes B6R and GW42 indicated numerous fractures over the length of the boreholes. Solution opening was present in borehole B6R at 749-753 FANGVD29.

Caliper

Three-arm caliper logs indicate enlargements in borehole diameter of more than 1 in. at about 689 and 754 FANGVD29 in borehole AW5D; from the bottom of the borehole to 758 FANGVD29 in borehole B6R; at about 757 FANGVD29 in borehole DF1S; at about 739 FANGVD29 in borehole DF2D; at about 731 FANGVD29 in borehole DF3; at about 755 and 790-813 FANGVD29 in borehole DF10; from the bottom of the borehole to about 719 FANGVD29 and at 810 FANGVD29 in borehole DF12; from the bottom of the borehole to about 708 FANGVD29 in borehole DF17; at about 782 and 752 FANGVD29 in borehole DF20; at about 795 FANGVD29 in borehole DF21; at about 700 FANGVD29 in borehole DF22; at about 717 FANGVD29 in borehole DF24; at about 750 FANGVD29 in borehole MW2; at about 767, 753,and 747 FANGVD29 in borehole PW3; and at about 789, 765, 745, 735, and 710 FANGVD29 at borehole SPW (table 5). Many of these enlarged areas are likely to be fractures or solutions openings. Fractures and solution openings indicated by caliper data usually also were indicated by lithologic and borehole camera logging. Caliper logs run in the remaining boreholes indicated little variation in diameter, indicating largely unfractured dolomite (U.S. Environmental Protection Agency, 1994).

Natural Gamma

Natural-gamma logs run in boreholes MW2, MW20, DF4D (fig. B1), DF11, and AW1D were compared to the stratigraphic descriptions for these boreholes obtained from analysis of the cores so the natural-gamma signal of the formations could be identified. Natural-gamma logs from these boreholes then were compared with natural-gamma logs from other boreholes so the stratigraphy across the Byron site could be determined. Comparison of the natural-gamma response with stratigraphy for each of the boreholes indicates that the Guttenberg Formation is approximately 5 ft thick beneath much of the southeastern part of the Byron site, but is reduced in thickness or absent in the western part of the BSY and the eastern part of the DFP, presumably because of erosion during the Ordovician system. Comparison of natural-gamma logs with stratigraphic delineation between boreholes indicates that the Galena-Platteville deposits dip to the south beneath the Byron site (figs. 9, 10).

Although the natural-gamma response typically shows a clear correlation with stratigraphy, anomalous responses were observed in some boreholes. Atypically high counts per second readings were detected at elevations of about 710 and 738 FANGVD29 in borehole SPW (fig. B2), 749 FANGVD29 in borehole B6R, and 709 FANGVD29 in borehole DF12 (fig. B3), which do not reflect the original bedrock stratigraphy. Anomalous responses on the natural-gamma logs correspond to areas where the borehole camera and caliper logs indicated the borehole was enlarged, indicating that these might be locations where fractures have been infilled with clays.

Spectral Gamma

Spectral-gamma logging in borehole SPW indicated amounts of uranium and thorium above background at 710 and 738 FANGVD29, whereas potassium was the dominant source of gamma radiation in other parts of the borehole (Frederick Paillet, U.S. Geological Survey, written commun., 1991). The difference in the clay mineralogy between the dolomite and the locations of the anomalous responses in the natural gamma logs indicates that the anomalous responses are caused by clay minerals infilling fractures (table 5).

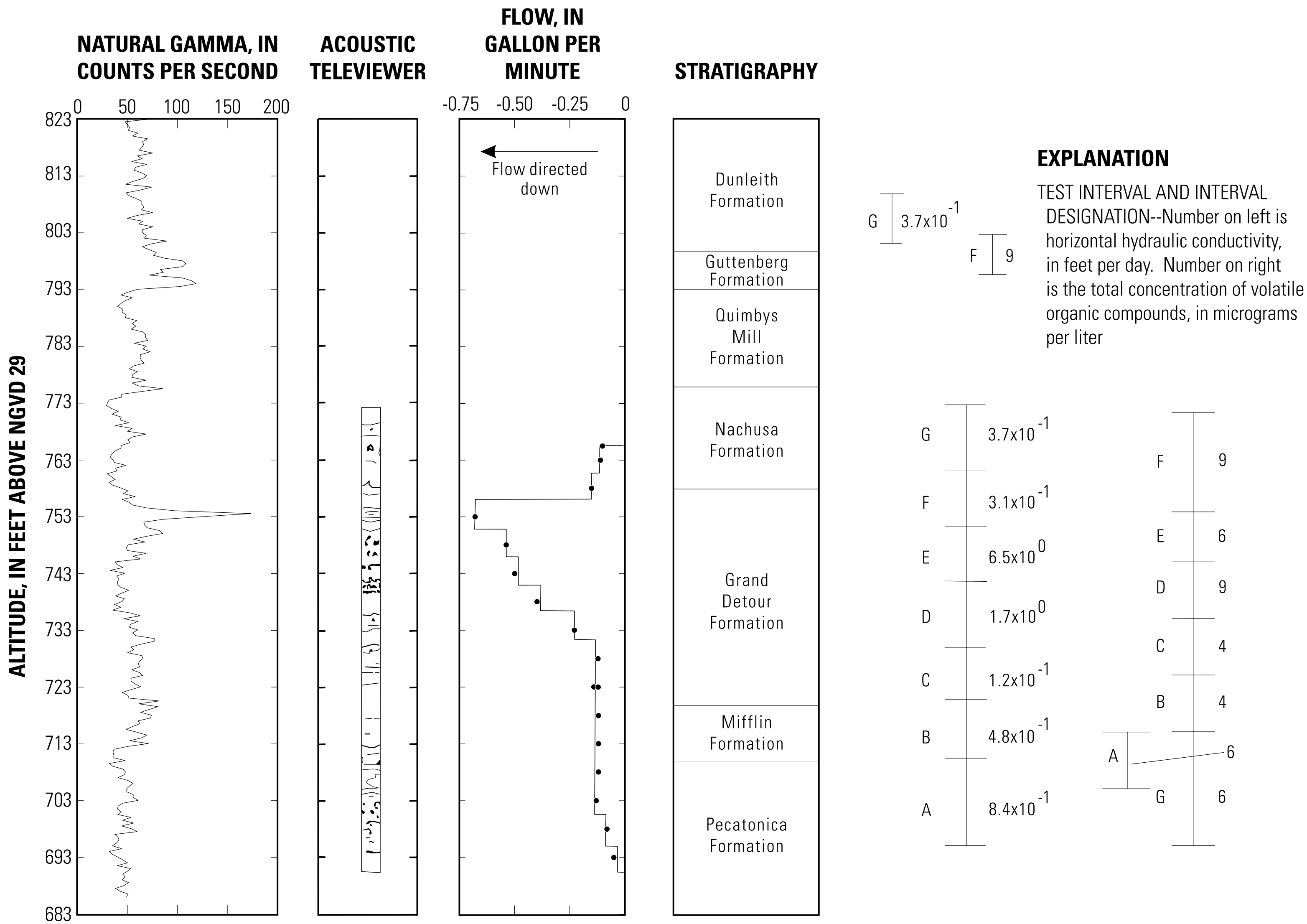

Figure B1. Natural-gamma, acoustic-televiewer, and flowmeter logs, stratigraphy, and horizontal-hydraulic-conductivity values and total concentration of volatile organic compounds in the test intervals isolated with a packer assembly for borehole DF4D, Byron site, Ill.

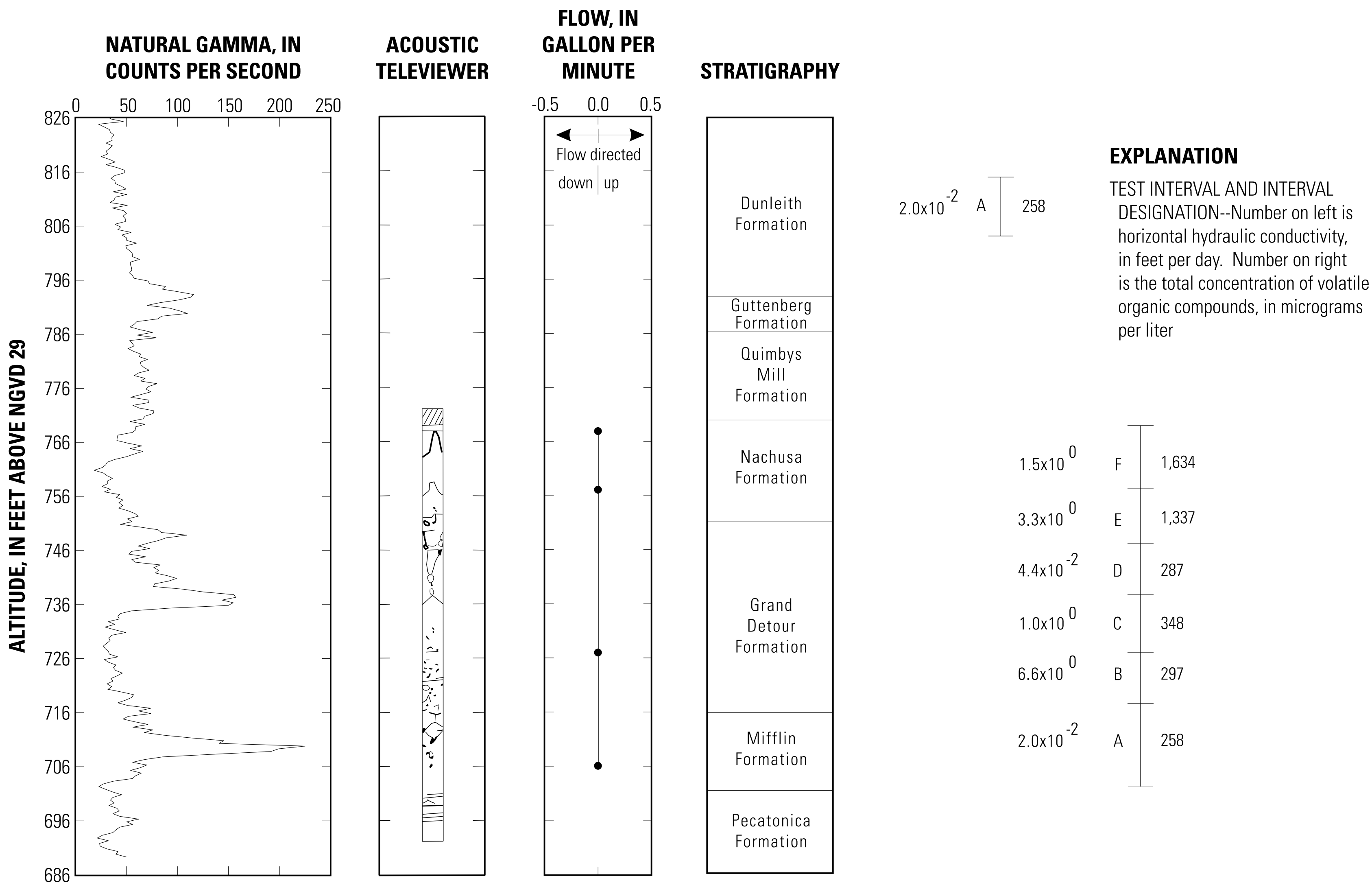

Figure B2. Natural-gamma, acoustic-televiewer, and flowmeter logs, stratigraphy, and horizontal-hydraulic-conductivity values and total concentration of volatile organic compounds in the test intervals isolated with a packer assembly for borehole SPW, Byron site, Ill.

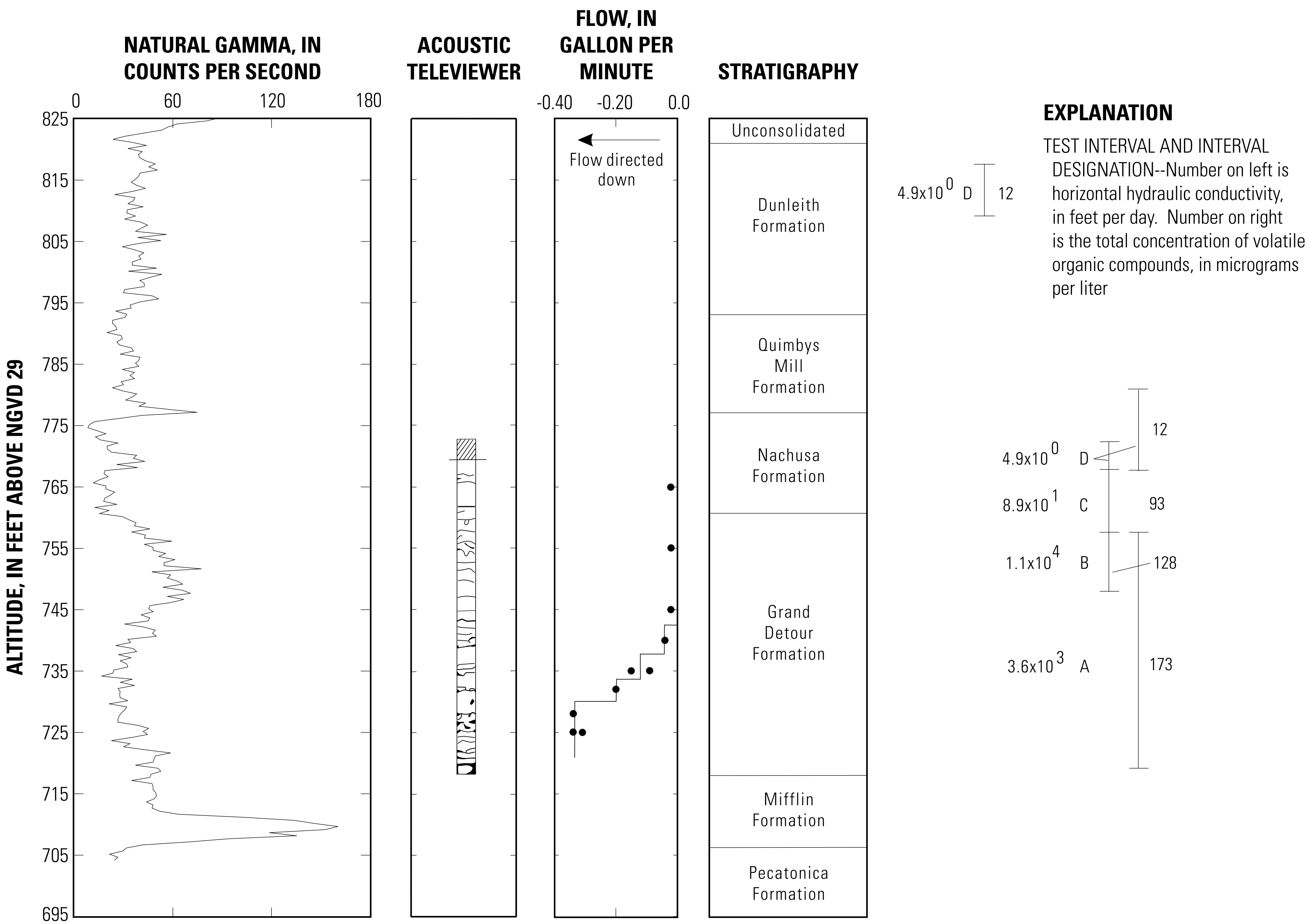

Figure B3. Natural-gamma, acoustic-televiewer, and flowmeter logs, stratigraphy, and horizontal-hydraulic-conductivity values and total concentration of volatile organic compounds in the test intervals isolated with a packer assembly for borehole DF12, Byron site, Ill.

Spontaneous Potential

SP logs indicated a gradual increase in signal response with depth below the top of the water surface in boreholes DF2D, DF4D, DF5D, DF12, DF17, and MW2, and a gradual decrease with depth in borehole PZ1 (U.S. Environmental Protection Agency, 1994). These logs indicated depths of alternating increasing and decreasing signal response in boreholes DF4S, DF5S, AW1D, and AW5D. SP logs tended to mirror natural-gamma logs, having high readings where natural-gamma values were high and low readings where natural-gamma values were low. Except for a large increase in signal associated with the possible fracture identified with the caliper logs at about 689 FANGVD29 in borehole AW5D, and a small increase associated with the possible fracture identified with lithologic and caliper logs near the bottom of borehole DF17, SP logs indicated no clear response to possible secondary-permeability features (table 5).

Single-Point Resistance

SPR logs indicated essentially no change in signal response in boreholes DF4D and DF5D; a gradual decrease in signal response with depth in boreholes DF4S, DF5S, DF12, and PZ3; and a sharp decrease near the possible fracture identified near the bottom of borehole DF17 (U.S. Environmental Protection Agency, 1994). Depths of alternating increasing and decreasing signal were identified in boreholes DF2D, DF4D, AW1S, AW1D, AW5D, PZ1, and MW2. Single-point-resistance logs tended to show an inverse relation with spontaneous-potential and natural-gamma logs, usually showing lower readings in areas where spontaneous-potential and natural-gamma values were higher and higher readings where spontaneous-potential and natural-gamma values were lower. Except for sharp decreases associated with the possible fracture identified with the caliper logs at about 689 FANGVD29 in borehole AW5D and near the bottom of borehole DF17, single-point-resistance logs indicated no clear response to areas of possible fractures (table 5).

Neutron

Neutron logs were run in boreholes MS2, B6R, GW16, GW42, MW10, MW11, MW16, MW18, MW20, PC2, DPW and SPW (table 3). Comparison of neutron logs and porosity measured from core samples at borehole MW20 indicated the expected inverse relation between porosity and neutron counts, but the neutron readings did not show a clear response at the depths of secondary-permeability features identified with other methods. This lack of identifiable response can be attributed partly to the effects of the variation in the clay mineral content of the dolomite. For example, the clay minerals that infilled some of the fractures in borehole SPW appear to have resulted in an increase in the counts per second response of the neutron log. Variations in the amount of condensate on the borehole walls above the water table, and variations in the moisture content in the unsaturated rock above the water table also may have affected the response of the neutron log in such a way as to obscure identification of secondary-permeability features. It also is possible that the porosity associated with many of the secondary-permeability features at the logged boreholes is small relative to the primary porosity, and the neutron log is not sensitive to these small porosity changes.

Acoustic Televiewer

Acoustic-televiewer logs indicate the presence of numerous thin (typically less than 0.25 ft thick), bedding-plane partings through the entire thickness of the Galena-Platteville aquifer below the water table. These bedding-plane partings likely are a combination of subhorizontal fractures related to carbonate solution or stratigraphic changes, and shale partings that have been removed from the borehole wall during drilling and borehole development. The goal of this and other investigations in the Galena-Platteville aquifer was to characterize permeable features and no effort was made to distinguish between subhorizontal fractures and bedding-plane partings. It is assumed, however, that bedding-plane partings are not appreciable pathways for ground-water flow and that fractures may be.

Acoustic-televiewer logging identified inclined fractures at various boreholes (tables 5, B1), including boreholes SPW (fig. B2), PZ1, PZ2, PZ3, AW1S, DF4D (table 5, fig. B1), and DF12 (table 4, fig. B3). Inclined fractures were identified at about 748, 738, and 698 FANGVD29 in borehole DF5D and at about 737 FANGVD29 in borehole DF13.

The inclined fractures at borehole DF13 and boreholes SPW, PZ1, PZ2, PZ3, and AW1S, which are located near the center of the BSY, have strikes that roughly are parallel to the dominant fracture orientation in the Galena-Platteville dolomite (N. 60° W) identified by Sargent and Lundy Inc., and Dames and Moore, Inc., (1975). Various fractures in the boreholes on the BSY are oriented parallel to the north-south and northeast-southwest trending fracture traces on the BSY (figs. 6, 8). The strike of the inclined fractures at boreholes DF4D and DF5D is about N 90° E, roughly parallel to the orientation of the nearby West Ravine (figs. 6, 8). The strike of the inclined fractures at borehole DF12 is roughly north-south, parallel to a nearby fracture trace (fig. 8).

Lithologic, caliper, and borehole-camera logs indicate the largest solution openings in boreholes DF12 and DF17 were near the bottom of the borehole. The bottom 5-10 ft of these boreholes was not logged because of concerns over the safety of the televiewer tool. As a consequence, solution openings were not identified with the televiewer logs in these boreholes in table 5.

Borehole Ground-Penetrating Radar—Single Hole

Single-hole directional GPR reflection surveys were done in eight boreholes (table 3) that were capable of about 30-60 ft of signal penetration into the dolomite (Niva, 1991a; Lane and others, 1994). The distance of signal penetration decreased with increasing depth, indicating increased conductivity with depth. Between three and six reflectors were identified from the processed data in the vicinity of the boreholes (table B1) (John Lane, U.S. Geological Survey, written commun., 1994). The reflectors identified at borehole AW1S are weak and may not actually be present in the rock.

The altitude of many (but not all) of the reflectors identified with the reflection surveys corresponded to the approximate altitude of stratigraphic contacts or fractures identified with other methods, indicating that many of the reflectors represent fractures or changes in lithology. The lithologic change is associated with the shale layer in the Grand Detour Formation. The absence of an identified fracture or lithologic change in a borehole at the altitude indicated by interpretation of the GPR reflection data does not necessarily indicate that the reflector is not present. The fracture or variation in lithology associated with the reflector may terminate before it intersects the borehole, its orientation may change, or the intersection may be above or below the bottom of the borehole.

The dip of the reflectors identified with the GPR reflection surveys ranges from about 24 to 65 degrees (table B1). The strike of the reflectors tends to be randomly oriented. Reflector orientation typically shows poor agreement with the orientation of the associated fractures determined with the acoustic-televiewer logs. Dip values determined from the reflection surveys tend to be substantially less than the values determined with the acoustic-televiewer logs. Strike values determined with the reflection surveys typically vary by more than 40 degrees from the strike values identified with the acoustic televiewer. These differences partly may be attributable to the differences in the amount of rock tested with the different methods, which could combine with variations in fracture extent and orientation in the rock so that features identified with the GPR may not be present, or may be present in the boreholes at different locations and orientations.

Borehole Ground-Penetrating Radar—Cross-Hole

Cross-hole GPR surveys done between the AW1S-PZ2, PZ2-PZ3 and PZ3-SPW borehole pairs indicate an upper zone of low velocity and high attenuation along all three profiles at about 735-740 FANGVD29 (figs. A5, A6). A lower zone of low velocity and high attenuation is present at about 710 FANGVD29 at borehole SPW, decreasing to about 690 ft near borehole PZ3 (Lane and others, 1994). The AW1S-PZ2 and PZ2-PZ3 borehole pairs are not deep enough to determine if the lower zone is present in these areas. The upper zone approximately corresponds to the argillaceous deposits in the upper part of the Grand Detour Formation. The lower zone approximately corresponds to a clay-filled fracture at borehole SPW (fig. B2) and a fractured parts of the Pecatonica Formation at borehole PZ3 identified with the geophysical logs. The lower zone appears to be continuous between boreholes SPW and PZ3.

Water-Level Measurements

Water levels were measured in monitoring wells and test intervals isolated with a packer assembly in select boreholes. Analysis of these measurements resulted in an improved characterization of the Galena-Platteville aquifer.

Continuous Measurements

During the investigations performed at the Byron site, water levels were measured in various wells on at least an hourly basis for periods of days or weeks to establish the processes affecting ambient water levels. Water levels in wells open to the Galena-Platteville aquifer in and near the BSY responded to changes in recharge from precipitation (Kay and others, 1999). Although an exhaustive analysis was not performed, water levels at well B3 essentially were unchanged during a period of unusually heavy precipitation in June and July 1993, whereas water levels in most of the other wells in the vicinity of the BSY rose between about 4 and 10 ft. Additionally, water levels in well B3 declined by less than 0.25 ft over a 10-day span as the aquifer recovered from the high water levels. Water levels in wells AW3 and B5 declined by more than 1.5 ft, and water levels in wells SPW, AW1S, AW1D, AW5D, B4, PW3, MW8, and MW9 declined by 2.5-5.5 ft during this 10-day period. The lack of response to precipitation in well B3 indicates that the part of the aquifer open to this well may be in poor hydraulic connection with the rest of the aquifer.

Table B1. Summary of inclined fracture orientations and reflectors in select boreholes by method of detection, Byron Superfund site, Ill.

[F, reflector interpreted to be a fracture; U, cause of reflection unknown; G, reflector interpreted to be a geologic contact; NI, not identified; NA, not analyzed; DNI, not projected to intercept borehole]

Borehole name (fig. 7)	Altitude or projected altitude of intersection with borehole (feet above National Geodetic Vertical Datum of 1929)	Fractures identified by acoustic televiewer		Reflectors identified by single-hole ground-penetrating radar		
		Strike (degrees from magnetic north)	Dip (degrees from horizontal)	Strike (degrees from magnetic north)	Dip (degrees from horizontal)	Interpreted cause of reflection
SPW	765	324	87	320	24	F
	756	270	83	NI	NI	
	752	315	39	NI	NI	
	745	120	87	NI	NI	
	737	288	77	100	37	F
	720	NI	NI	NA	53	U
	711	126	77	250	44	F
	703	135	87	NI	NI	
PZ1	764	NI	NI	120	61	U
	750	108	39	NI	NI	
	749	108	22	NI	NI	
	746	126	31	NI	NI	
	740	270	45	NI	NI	
	735	171	72	210	32	F
	718	NI	NI	70	51	F
	708	NI	NI	190	27	F
	688	198	31	NI	NI	
PZ2	787	NI	NI	10	37	G
	775	216	85	260	44	F
	763	315	86	NI	NI	
	715	288	73	40	46	G
PZ3	784	NI	NI	200	46	U
	768	0	11	NI	NI	
	744	0	31	90	44	F
	741	315	54	NI	NI	
	737	315	58	NI	NI	
	719	306	77	NI	NI	
	716	153	84	NI	NI	
	709	333	67	NI	NI	
	702	153	78	NI	NI	
	694	153	80	NI	NI	
	681	NI	NI	250	58	U
	677	NI	NI	280	33	G
	643	NI	NI	170	65	
AW1S	787	NI	NI	NA	27	G
	777	18	63	NI	NI	
	776	117	76	NA	34	G
	766	27	80	80	42	F
	DNI	NI	NI	270	89	U

Water levels in wells open to the Galena-Platteville aquifer in and near the BSY also responded to changes in barometric pressure (U.S. Environmental Protection Agency, 1994; Kay and others, 1999). Water levels in well AW5I indicated instantaneous fluctuations in response to changes in barometric pressure during monitoring in July 1993 (fig. A7). The barometric efficiency of well AW5I varied substantially depending on which data measurements used, but averaged 107 percent. Wells B3, B5, AW3, AW6, MW8, and MW9 indicated less response to barometric changes. Additional monitoring of barometric pressure and water levels over a 3-day period in October 1989 indicates that water levels in well AW1S show a substantial response to variations in barometric pressure, well B3 less so, and well AW1D appears to be unaffected by the 15 millibar change in barometric pressure. The barometric efficiency of a well is inversely related to its storage coefficient (Jacob, 1940), which is affected by whether the aquifer is confined or unconfined (Rasmussen and Crawford, 1996). Therefore, the response to barometric pressure indicates the storage coefficient of the Galena-Platteville aquifer is low at well AW5I, which is indicative of a confined part of the aquifer. The moderate response to barometric pressure indicates the storage coefficient of the Galena-Platteville aquifer is intermediate at water-table wells AW1S, B5, AW3, AW6, MW9, and B3, and deep well MW8, indicating that the aquifer may be unconfined at the screened interval of these wells. The response to barometric pressure indicates the storage coefficient of the Galena-Platteville aquifer is high at well AW1D, indicating unconfined conditions. However, other data indicate that the aquifer is confined at well AW1D and the lack of water-level response to barometric pressure at this well may be because of well storage, skin effects, or low aquifer permeability.

Periodic Measurements

Water levels were collected periodically from the available wells from 1985 to 1999. The most frequent monitoring occurred during 1985-92. With the exception of wells B3 and MS1, water levels in the wells with a period of record prior to 1990 varied by 10-20 ft. Water levels in wells B3 and MS1 varied by less than 10 ft from 1985 to 1999, whereas annual variations typically were about 10 ft for the remaining wells (fig. B4). The data are insufficient to clearly evaluate seasonal trends or the relation between water levels and precipitation. The small fluctuation in water levels at well MS1 may be related to its position in the downgradient part of the Galena-Platteville aquifer at the Byron site. The small fluctuation in water levels at well B3 indicates that this well may monitor an area in poor hydraulic connection with the rest of the aquifer.

Water levels at well clusters open to the water table and the middle or base of the Galena-Platteville aquifer typically increased and decreased at the same time and typically by similar amounts (fig. B4). These patterns indicate that the Galena-Platteville aquifer has sufficient hydraulic interconnection to respond to hydraulic effects as a single aquifer.

Water levels from most of the periods of measurement were used to construct the water-table configuration and the potentiometric surface at the bottom of the Galena-Platteville aquifer so that a three-dimensional representation of flow directions could be obtained. Water-level data collected on May 11 and 12, 1992 (figs. 13, 14), are representative of typical hydraulic conditions and are used to illustrate ground-water-flow directions and gradients.

The water-table configuration in the Galena-Platteville aquifer generally mirrors surface topography. The overall direction of flow is toward the Rock River, with components of flow toward the topographic lows at Woodland Creek and the West Ravine (fig. 13). Water-level data indicate that a ground-water divide is present along the topographic ridge, a ground-water sink is present at the topographic lows at Woodland Creek and the West Ravine, and the Rock River is the point of discharge. Based on the water-table configuration, the Galena-Platteville aquifer underlying the southeastern part of the Byron site can be divided into four zones on the basis of the altitude and configuration of the water table (fig. 13). Transitional areas are present between zones.

Zone 1 corresponds primarily to the part of the aquifer where the water table is above 770 FANGVD29 beneath much of southeastern part of the Byron site (fig. 13). Zone 2 is characterized by a flat part of the water table from about 745 to 770 FANGVD29. Zone 2 is located northwest of zone 1 and intersects with zone 1 in the southwestern part of the BSY. Zone 3 is a subset of zone 2, and consists of a small area northwest of the BSY, where water levels virtually are identical. Zone 4 is defined by water-level altitudes typically less than 750 FANGVD29 near Woodland Creek and less than 730 FANGVD29 near the West Ravine. Zone 4 is an area of lower land-surface altitude.

Variations in the water-table altitude in fractured-rock aquifers reflect variations in the permeability distribution and topography (LeGrand and Stringfield, 1971). The high water table at zone 1 indicates that this is a zone of low permeability and a low degree of fracture interconnection, requiring high hydraulic gradients to move water. This interpretation is consistent with the results of geophysical and lithologic logging, which indicate that the Galena-Platteville aquifer is composed of generally competent dolomite in this zone, particularly in the upper part of the aquifer, although permeable features are present locally. Geophysical logs and core analysis indicate zone 1 may correspond to areas where the Guttenberg Formation is thickest and most competent. Intermediate water levels in zones 2 and 3 and data from lithologic and geophysical logging indicate a well-developed system of permeable interconnected fractures and solutions openings (karstic features) in these zones, particularly in zone 3. Ground-water flow in this area is through a well-developed system of fractures and solution openings requiring low hydraulic gradient to move water. The low water table in zone 4 coupled with comparatively large decreases in surface topography and data from the lithologic logging, core analysis, and presence of the fracture traces indicate ground-water flow in zone 4 also is through a well-developed fracture network.

The potentiometric surface at the base of the Galena-Platteville aquifer indicates the same general horizontal flow directions are present as shown in the water-table surface (fig.14). However, the potentiometric surface at the base of the aquifer is not as complex as the water-table configuration, indicating that the bottom of the aquifer is more homogenous than the upper part.

Vertical changes in water level between the water table and the base of the Galena-Platteville aquifer typically are more than 50 ft in zone 1, but always are less than 10 ft, and typically less than 2 ft in the other zones. With the exception of the area of wells DF22S and D in the southern part of the DFP (fig. 14), water levels indicate the potential for downward flow (table 4). High vertical-hydraulic gradients at zone 1 indicate that the vertical-hydraulic conductivity of the aquifer in this area is high in comparison to zones 2, 3, and 4 and that a confining unit may be present in zone 1.

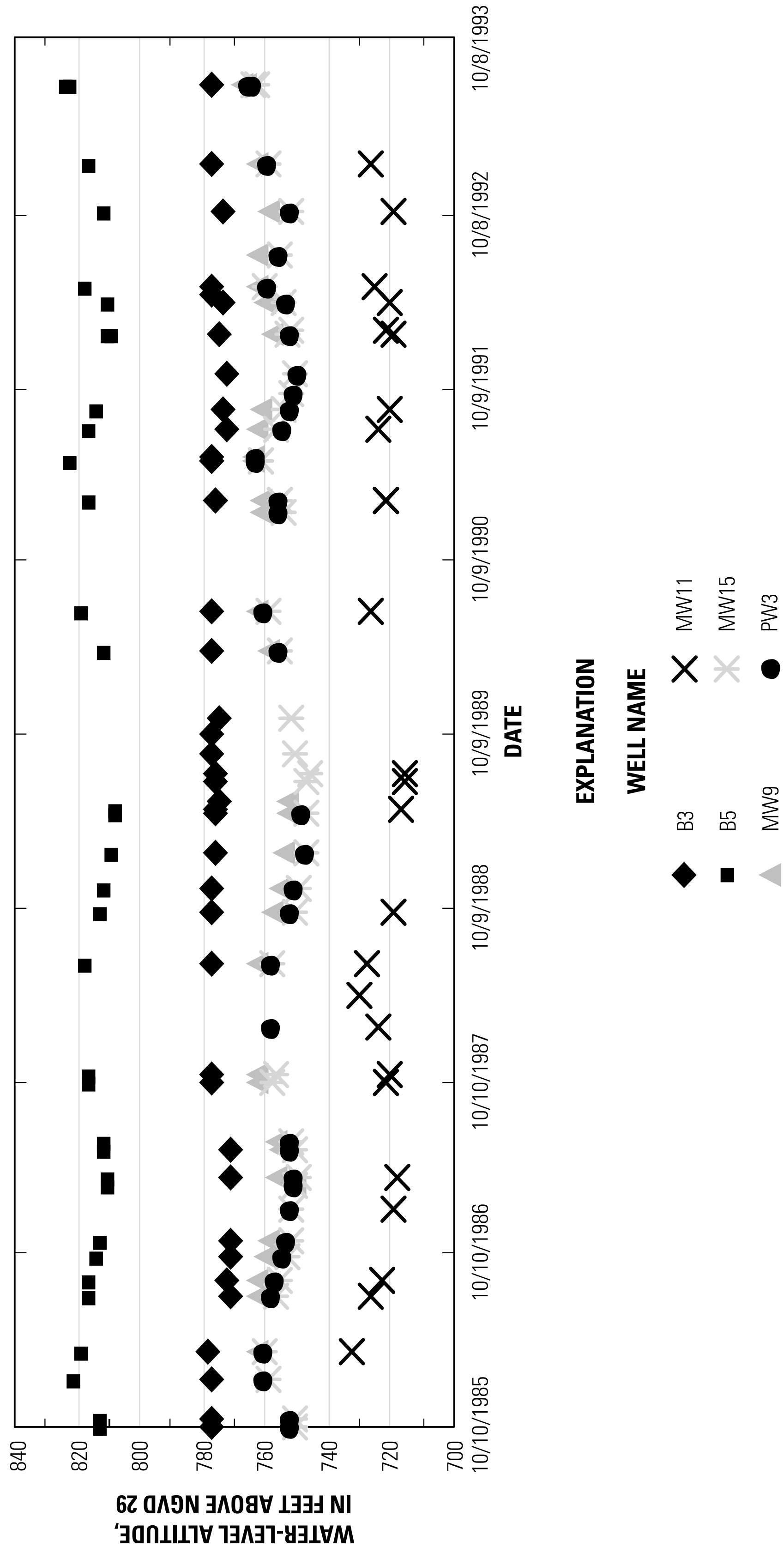

Figure B4. Water-levels in select monitoring wells, Byron site, Ill., October 1985–July 1993.

Single Measurements-Packers

Test intervals isolated with the packer assembly sampled most or all of the saturated thickness of the aquifer at boreholes DF5D, DF12, DF13, SPW, AW1S, and PZ1. Water levels did not equilibrate during testing in various intervals from boreholes DF2D, DF4D, DF6, and DF14D because of slow recovery rates and data from these boreholes could not be used. Slow recovery rates in these boreholes indicate low aquifer permeability.

Water levels measured above, within, and below the test intervals indicate the potential for downward flow within the aquifer at boreholes DF5D, DF12, DF13, SPW, AW1S, and PZ1 and the potential for upward flow near borehole DF17 (table B2). Water levels above and below the test intervals typically differed by more than 20 ft in at least one test interval in boreholes DF5D, AW1S, and PZ1. Water levels above and below the test intervals differed by about 2 ft in the one test interval from borehole DF17 and by at least 0.40 ft at borehole DF12. Water levels above and below the test intervals typically differed by less than 0.15 ft in all of the test intervals in boreholes DF13 and SPW.

Water levels measured in some boreholes differed substantially from the water levels measured in test intervals isolated with a packer assembly. Borehole AW1S is open to the aquifer from 826 to 750 FANGVD29. The water level in this borehole was 780.99 FANGVD29 prior to insertion of a packer assembly. When test interval A (from 765 to 750 FANGVD29) was isolated, the water level in the test interval fell about 13 ft to 767.63 FANGVD29, whereas the water level above the test interval rose about 23 ft to 803.93 FANGVD29 (table B2). These data indicate that the water level in borehole AW1S is lower than the actual water-table altitude. It is probable that water levels in wells MW3, AW2, and MW1 also do not accurately reflect the actual water table.

Borehole DF5D is open to the Galena-Platteville aquifer from about 690 to 830 FANGVD29. Water levels in the borehole and in that part of the aquifer above the test interval were about 756 FANGVD29, when the test intervals below about 739 FANGVD29 were isolated (test intervals A-D)(table B2). This water level (756 FANGVD29) is similar to the water level within the test interval when the test intervals included that part of the borehole between 726 and 739 FANGVD29 (test intervals E-G). The water level above (for interval G) or within (for intervals H and I) the test intervals increased to over 767 FANGVD29 when that part of the aquifer above 739 FANGVD29 was isolated. Similar results were observed in the packed intervals above 742 FANGVD29 at borehole PZ1.

Because the water level in an open borehole is affected by the vertical distribution of water levels and Kh in the aquifer along the open interval of the borehole (Sokol, 1963), water-level data from test intervals isolated with a packer assembly can provide insight into the secondary-permeability network at a site. The high vertical-hydraulic gradients in the upper part of the aquifer at boreholes AW1S, DF5D, and PZ1 indicate parts of the aquifer with low vertical hydraulic conductivity and the presence of few secondary-permeability features with minimal vertical interconnection. The effect of secondary-permeability features at 726-739 FANGVD29 in borehole DF5D and at 742 FANGVD29 in borehole PZ1 on the water level in these boreholes indicates that these are the most permeable features at these boreholes, and that these features are in poor hydraulic connection with the overlying parts of the aquifer (table B2). The low (less than 0.10 ft/ft) vertical hydraulic gradients observed during packer testing at boreholes DF12, DF13, DF17, and SPW (table B2) indicate that the Galena-Platteville aquifer has good vertical hydraulic connection at these boreholes. These conclusions are consistent with the analysis of the periodic water-level monitoring at the Byron site. Boreholes PZ1 and DF5D are in that part of the aquifer corresponding to zone 1. Boreholes DF12, DF13, and DF17 are in zones 3, 4, or transitional areas of the aquifer. Borehole SPW is located in zone 1; however, this borehole intercepts a vertical fracture, which likely transmits water vertically through the aquifer.

Geophysical Logs

Geophysical logs also were run in various boreholes to determine the presence of permeable features (fractures, vugs, solution openings) in the Galena-Platteville aquifer beneath the Byron site (table 3).

Temperature

Water temperatures measured with the geophysical logs indicated little variation, ranging from about 10.5 to 11.0^{o}C in most boreholes. Water temperature in boreholes AW1S and MW2 increased gradually with depth, but indicated no changes indicative of inflowing or outflowing water. Water temperature indicated a slight change in gradient at about 702 FANGVD29 and perhaps at about 674 FANGVD29 in borehole AW1D and at about 690 FANGVD29 in borehole PZ3. These altitudes might correspond to the location of permeable features. Water temperature indicated an abrupt increase with depth just below a possible fracture identified on the caliper log at about 690 FANGVD29 in borehole AW5D, and at about 725 FANGVD29 in borehole PZ1 (table 6), indicating that these features are permeable.

Table B2. Water-level data in select test intervals isolated with a packer assembly, Byron Superfund site, Ill.

(NA, not applicable; NT, not taken; >, greater than; NE, not equilibrated)

Borehole name (fig. 7)	Test interval	Altitude of test interval (feet above National Geodetic Vertical Datum of 1929)	Water-level altitude (feet above National Geodetic Vertical Datum of 1929)		
			Above test interval	In test interval	Below test interval
AW1S	A	751-766	803.93	767.63	NA
AW1S	B	785-804	NA	804.12	NT
DF5D	A	674-691	756.32	754.41	NA
DF5D	B	691-701	756.28	756.12	755.14
DF5D	C	701-711	756.31	756.17	756.14
DF5D	D	711-721	756.35	NT	756.20
DF5D	E	721-731	756.22	756.19	756.05
DF5D	F	731-753	NA	756.24	756.20
DF5D	G	731-741	767.92	756.02	756.02
DF5D	H	745-777	NA	776.02	755.79
DF5D	I	770-778	NA	777.42	765.07
DF12	A	702-741	759.87	759.87	NA
DF12	B	731-741	759.87	759.83	NT
DF12	C	741-751	>760.30	759.91	NT
DF12	D	751-755	NA	759.85	NT
DF13	A	680-695	764.02	763.95	NA
DF13	B	695-705	NE	NE	NE
DF13	C	705-715	763.58	763.54	763.52
DF13	D	715-725	763.67	763.64	763.61
DF13	E	725-735	NT	763.60	763.54
DF13	F	735-745	NE	NE	NE
DF13	G	736-766	NA	764.80	764.50
DF17	A	698-715	736.78	738.73	NA
DF17	B	715-725	736.87	NT	738.74
DF17	C	725-733	NA	736.79	NT
PZ1	A	671-687	753.85	754.00	NA
PZ1	B	687-697	753.91	753.81	754.23
PZ1	C	694-704	753.93	753.83	754.41
PZ1	D	704-714	754.31	753.86	753.80
PZ1	E	714-724	754.39	754.04	754.05
PZ1	F	724-734	759.58	755.03	755.03
PZ1	G	734-744	758.64	755.09	755.14
PZ1	H	744-754	791.54	758.84	>755.51
SPW	A	686-702	NT	NT	NT
SPW	B	702-712	754.13	754.05	NA
SPW	C	712-722	753.68	753.58	NT
SPW	D	722-732	753.58	753.56	NT
SPW	E	732-742	NT	NT	NT
SPW	F	742-751	NA	753.56	NT

Fluid Resistivity

Fluid-resistivity values measured in boreholes DF2D, AW1S, AW1D, AW5D, MW2, PZ1, and PZ3 typically were about 1,500 to 2,000 μmho/cm. Resistivity values in boreholes DF2D and MW2 decreased gradually with depth and indicated no changes indicative of water flowing into or out of the borehole. Resistivity values indicated an increase of about 20 μmho/cm at 792 ft at borehole AW1S, and a slight change in slope at about 727 FANGVD29 in borehole PZ1 (table 6) and at about 796 FANGVD29 in borehole PZ3. These depths may correspond to permeable features. Resistivity values indicated an abrupt decrease of approximately 25 μmho/cm with depth near a possible fracture identified on the caliper log at about 690 FANGVD29 in borehole AW5D, indicating that the possible fracture is permeable. Fluid-resistivity values indicated a gradual decrease of approximately 50 μmho/cm with depth at about 727 FANGVD29 at borehole AW1D, increased by about 2,000 μmho/cm to a maximum value at about 687 ft, then decreased steadily by about 1,500 μmho/cm to the bottom of the borehole at 672 ft. There may be permeable features at 672-687 FANGVD29, and 687-727 FANGVD29 at borehole AW1D.

Flowmeter Logging—Single Hole

Flowmeter logging under conditions of ambient flow in borehole DF4D indicates downward flow in the borehole with water cascading down the borehole to the top of the water column at 766 FANGVD29 and inflow along a subhorizontal bedding-plane parting near the top of the Grand Detour Formation at 757 FANGVD29 (table 6)(fig. B1). Outflow was detected through a series of bedding-plane partings, inclined fractures, and vugs in the upper to middle parts of the Grand Detour Formation between about 753 and 728 FANGVD29 and the middle part of the Pecatonica Formation below about 700 and 690 FANGVD29.

Flowmeter logging under ambient-flow conditions in borehole DF5D indicates downward flow in the borehole with water draining down the borehole to the top of the water column at 762 FANGVD29 and, possibly, inflow from one or more bedding-plane partings between 762 and 759 FANGVD29. Outflow was detected through a series of bedding-plane partings, inclined fractures, and vugs in the lower half of the Grand Detour Formation between about 739 and 729 FANGVD29. No flow was detected below 729 FANGVD29.

Flowmeter logging under ambient-flow conditions in borehole DF12 indicates downward flow in the borehole with inflow through vugs and fractures in the lower part of the Grand Detour Formation from about 741 through 728 FANGVD29 (table 6)(fig. B3). Concerns over equipment safety prevented obtaining a flowmeter measurement below 723 FANGVD29 in this borehole, but in order for inflow to be present in the upper part of the borehole, outflow must have been present below 723 FANGVD29.

Vertical flow was not detected under ambient-flow conditions in borehole DF13. Water-level data collected during packer testing identified less than 0.10 ft difference in water levels between the upper and lower parts of this borehole (table B2), indicating that the lack of ambient flow results from an absence of vertical hydraulic gradient within the borehole. Flowmeter logging done in conjunction with pumping from borehole DF13 identified flow associated with bedding-plane partings in the Grand Detour Formation at 759 and 734-732 FANGVD29, a vuggy part of the Grand Detour Formation at 747 FANGVD29, and bedding-plane partings in the Pecatonica Formation at about 702 FANGVD29.

Flowmeter logging under ambient-flow conditions in borehole DF17 indicates upward flow in the borehole with inflow through permeable fractures or solution openings in the Pecatonica Formation below 710 FANGVD29. Outflow is through bedding-plane partings in the Grand Detour Formation at about 730 and 735 FANGVD29 (table 6).

Vertical flow was not detected under ambient-flow conditions in borehole SPW (fig. B2). Water-level data collected during packer testing identified less than 0.11 ft difference in water levels between the upper and lower parts of this borehole (table B2), indicating that the lack of ambient flow results from an absence of enough vertical variation in water level within the borehole to drive flow. The lack of vertical variation in water level at borehole SPW may be attributed to good vertical hydraulic connection within the inclined fractures that intercept the borehole. Flowmeter logging done in conjunction with pumping in borehole SPW identified measurable flow through the inclined fractures in the Grand Detour Formation above 736 FANGVD29 and through the inclined fracture in the Mifflin Formation at about 711 FANGVD29 (Frederick Paillet, U.S. Geological Survey, written commun., 1993). About 0.03 gal/min of flow occurred through one or more bedding-plane partings in the Pecatonica Formation at about 698 FANGVD29. Single-hole reflection surveys identified a reflector at about 711 FANGVD29 in borehole SPW, but no reflectors were identified near the other permeable intervals. The interval at 711 FANGVD29 approximately corresponds to the depth of the lower zone identified at borehole SPW on the cross-hole tomograms. This result indicates the lower zone is a permeable subhorizontal fracture and that it may extend from boreholes PZ3 and SPW to borehole PZ1. This fracture shows no clear relation to changes in lithology.

Flowmeter logging under ambient-flow conditions in borehole PZ1 indicates downward flow, with water cascading down the borehole to the top of the water column and, possibly, inflow from fractures at or near the highest point of flow measurement at 748 FANGVD29 (Frederick Paillet, U.S. Geological Survey, written commun., 1993, 1997)(table 6). Outflow was through a vuggy, fractured part of the aquifer in the Mifflin Formation (fig. 11) at an altitude of about 708 FANGVD29. The altitude of the outflow interval corresponds to one of the reflectors identified from the single-hole radar survey (table B1). The altitude of the outflow interval also is consistent with the altitude of the lower zone identified at borehole SPW on the cross-hole tomograms (figs. A5, A6; table 5).

Flowmeter logging under ambient-flow conditions in borehole PZ2 indicates downward flow, with water draining down the borehole to the top of the water column and, possibly, inflow from a series of fractures above the highest point of measurement at 784 FANGVD29. Outflow was through inclined or horizontal fractures in the Nachusa Formation at an altitude of about 761 FANGVD29, one or more horizontal fractures in the Grand Detour Formation between 748 and 754 FANGVD29, and a fracture at about 723 FANGVD29. Single-hole reflection data identified a reflector at 787 FANGVD29 in this borehole but no reflectors were identified at the other depths of flow (table B1).

Flowmeter logging under ambient-flow conditions in borehole PZ3 indicates downward flow, with water draining down the borehole to the top of the water column and, possibly, inflow from some of the horizontal fractures near 764 FANGVD29. Inflow was through a horizontal fracture in the Grand Detour Formation at 750 FANGVD29. Outflow was through horizontal and inclined fractures in the Pecatonica Formation at about 694 FANGVD29. Single-hole reflection data identified a reflector at 746 FANGVD29 in this borehole, but no reflectors were identified that clearly correspond to depths of measurable flow. The outflow interval near 694 FANGVD29 approximately corresponds to the altitude of the lower zone identified at borehole PZ3 on the cross-hole tomograms.

Flowmeter logging under ambient-flow conditions in borehole AW1S gave inconsistent readings between multiple measurements at the same depth and at different depths in the borehole, but indicated less than 0.10 gal/min of downflow in the borehole. The small amount of flow coupled with the lack of consistent readings precludes identification of specific depths of flow into or out of this borehole. The large water-level differences measured during packer testing in this borehole indicate that the small amount of flow measured is the result of uniformly low aquifer permeability at this borehole.

Flowmeter Logging—Cross-hole

Flowmeter logging in boreholes PZ1, PZ2, and AW1S was done in conjunction with pumping in borehole SPW at 22 gal/min, and in borehole PZ3 at 32 gal/min (Frederick Paillet, U.S. Geological Survey, written commun., 1993). Analysis of changes in flow in response to pumping resulted in identification of flow pathways between boreholes.

Analysis of changes in the flow in borehole PZ1 during pumping in borehole SPW indicates hydraulic connection between the permeable feature at about 708 FANGVD29 in borehole PZ1 and one or more fractures supplying the water pumped from borehole SPW (table 6). Analysis of flow in borehole PZ2 during pumping in borehole SPW indicates hydraulic connection between the fractures from 748 to 754 FANGVD29 and, possibly, the horizontal or inclined fracture at about 761 FANGVD29 in boreholes PZ2 and SPW. Analysis of changes in flow in borehole PZ3 during pumping in borehole SPW indicates hydraulic connection between the fractures at about 764, 750, and 694 FANGVD29 at borehole PZ3 and one or more fractures supplying water to borehole SPW. No changes in flow were observed in borehole AW1S during pumping in borehole SPW.

Analysis of changes in the flow in borehole PZ2 during pumping in borehole PZ3 indicate hydraulic connection between the horizontal fractures above 784 FANGVD29, and at 748-754 FANGVD29 in borehole PZ2 and one or more fractures supplying the water pumped from borehole PZ3. No changes in flow were observed in borehole AW1S, SPW, and PZ1 during pumping in borehole PZ3.

Flowmeter, acoustic televiewer, and borehole-radar data in the vicinity of boreholes SPW, PZ1, PZ2, PZ3, and AW1S indicate inclined fractures that intercept the borehole above 736 FANGVD29 and at 711 FANGVD29 supply most of the water to borehole SPW. These fractures are connected hydraulically to an upper flow pathway at about 750 FANGVD29 and a lower flow pathway below 711 FANGVD29 (figs. A5, A6). The upper flow pathway appears to correspond to a number of horizontal fractures in the upper part of the Grand Detour Formation. These fractures are above the argillaceous deposits of the Grand Detour Formation identified as the upper zone by the cross-borehole tomography and are overlain by a low-permeability interval. The upper flow pathway may be absent near borehole AW1S. The lower flow pathway appears to correspond to a fractured interval that extends between boreholes SPW and PZ1, between 711 and 708 FANGVD29, and between boreholes SPW and PZ3, between 711 and about 694 FANGVD29. The lower flow pathway appears to correspond to the lower permeable zone identified with the cross-hole logging and corresponds to the Mifflin and Pecatonica Formations.

Flowmeter logging was done in boreholes DF13 and DF5D during pumping in borehole DF4D at 6.5 gal/min. Borehole DF13 had a slight increase in flow between 742 and 721 FANGVD29, indicating flow between the permeable features supplying water to borehole DF4D and permeable features in the lower portion of the Grand Detour Formation at borehole DF13. Borehole DF5D did not respond to pumping in borehole DF4D.

Hydrophysical Logging

Hydrophysical logging under ambient-flow conditions in borehole DF4D indicated flow down the borehole wall to the top of the water column, flow into the borehole through subhorizontal bedding-plane partings at about 754, 739-743, 729, and 694-698 FANGVD29 (GZA Geoenvironmental, Inc., 1991)(table 6). Hydrophysical logging indicates the specific conductance of the permeable features above 729 ft was about 840 µS/cm, whereas the specific conductance of the permeable feature from 694 to 698 ft was about 600 µS/cm. This interpretation is consistent with that made from analysis of the single-borehole GPR survey, which indicated decreased fluid conductivity with depth at this borehole.

Hydrophysical logging under ambient-flow conditions in borehole DF12 identified inflow through the fractures and solution openings below about 713 FANGVD29 (table 6). Hydrophysical logging under conditions of ambient flow in borehole SPW did not detect vertical flow, presumably because of a lack of vertical variation in water level within the aquifer. Hydrophysical logging, done in conjunction with simultaneous pumping and fluid injection in borehole SPW, identified inflow through inclined fractures at about 711 and 744 FANGVD29 (table 6). Hydrophysical logging indicates the specific conductance of the permeable feature at 711 FANGVD29 was about 1,035 µS/cm, whereas the specific conductance of the permeable feature at 744 FANGVD29 was about 725 µS/cm. This interpretation is different from that made from analysis of the single-borehole GPR survey that indicated decreased fluid conductivity with depth at this borehole.

Aquifer Tests

Slug tests, specific-capacity tests, step-drawdown tests, multiple-well tests, and tracer tests were performed at the Byron site (table 3). The results of these tests confirm and expand upon interpretations of hydrogeologic conditions determined with the application of other methods.

Slug Tests

Kh values were obtained from slug tests in 55 monitoring wells open to the Galena-Platteville aquifer at the Byron site and in 55 test intervals isolated with a packer assembly that sampled most of the aquifer thickness at wells AW1S, DF2D, DF4D, DF5D, DF6, DF12, DF13, DF14D, PZ1, and SPW. Kh values ranged from a high of 11,000 ft/d in test interval B of borehole DF12 to a low of 0.0034 ft/d in test interval A of borehole DF14D. The large variation in Kh supports the conclusion that the Galena-Platteville aquifer is highly heterogeneous.

The geometric mean of the Kh values was calculated for each of the four zones in the Galena-Platteville aquifer identified from analysis of the water-table configuration (fig. 13). The mean Kh in zones 1,2,3, and 4 was 0.31, 5.2, 240, and 8.0 ft/d, respectively. The median Kh in the upper part of zone 1 is 0.11 ft/d, slightly lower than the mean Kh in the lower and middle parts of zone 1 (0.48 ft/d). These conclusions are consistent with those drawn from analysis of the lithologic and flowmeter logs, water levels in test intervals isolated with a packer assembly, and the water-table configuration.

Kh values obtained from the slug tests in the intervals isolated with a packer assembly in a borehole or in the finished monitoring wells were compared to the stratigraphic unit to which the well or test interval was open. The geometric mean of the Kh for the Galena Group is 0.12 ft/d (fig. 12). The geometric mean of the Kh for the Pecatonica, Nachusa, and Quimbys Mill Formations varied from 0.23 to 0.62 ft/d. The geometric mean of the Kh for the Mifflin and Grand Detour Formations is 1.3 and 2.7 ft/d, respectively. If the values determined for wells DF12 and MW16 northwest of the BSY are excluded, the mean Kh of the Mifflin Formation is calculated to be 0.71 ft/d, indicating the Kh of the Mifflin Formation is not appreciably higher than that of the Pecatonica, Nachusa, and Quimbys Mill Formations beneath most of the Byron site. The higher mean Kh of the Grand Detour Formation across the Byron site is consistent with the presence of collapse features in this formation observed at the Benesh Quarry.

Comparison of Kh values for test intervals obtained by use of the packers with the elevation of permeable features identified from the flowmeter logs generally show good to moderate correlation (table 6)(figs. B1, B2, B3). The correlation was more consistent between intervals of low permeability identified from the slug tests and the flowmeter logs. For example, Kh values in borehole AW1S are less than 0.05 ft/d, and no permeable intervals were identified with the flowmeter logs.

Flowmeter logs and slug-test values show generally good agreement at borehole DF5D, where flowmeter logs indicate the presence of permeable features between about 739 and 729 FANGVD29 and, perhaps, 762 and 759 FANGVD29. A Kh of 18 ft/d was calculated between 721 and 731 FANGVD29, and a value of 3.2 ft/d was calculated between 731 and 741 FANGVD29. Kh values for the remaining test intervals were less than 0.10 ft/d, including the test interval corresponding to the possible permeable feature at about 762 FANGVD29. The differences in interpretation in aquifer permeability at about 762 FANGVD29 can be attributed to the flowmeter log measuring inflow of water cascading down the borehole to the top of the water column, not inflow from a permeable fracture in this interval.

Flowmeter logs indicate the presence of permeable features at borehole DF4D at 690-700, 728-753, and 757 FANGVD29 (table 6)(fig. B1). Kh values greater than 1.5 ft/d were calculated between 721 and 741 FANGVD29, whereas Kh values less than 0.90 ft/d were calculated in the 683-698 interval, and Kh values less than 0.50 ft/d were calculated in all of the remaining test intervals, including the 751-762 interval. The presence of measureable flow in intervals of comparatively low Kh near the top and the bottom of borehole DF4D may be a reflection of the large variation in water level over the length of the borehole.

Although the saturated thickness of the Galena-Platteville aquifer at borehole DF12 was about 12 ft less during slug testing than during flowmeter logging, analysis of slug tests and flowmeter logs both indicate the presence of permeable features from approximately 728-741 FANGVD29 and between the bottom of the borehole at 703 FANGVD29 and the lowest flowmeter measurement at 723 FANGVD29 (fig. B3). Slug-test results indicate high (greater than 4.0 ft/d) Kh above 741 FANGVD29, whereas a change in flow in this interval was not detected by the flowmeter log. This discrepancy is most likely because the Kh of the aquifer above 741 FANGVD29 is more than two orders of magnitude less than it is from 731 to 741 FANGVD29 (11,000 ft/d), precluding effective measurement of changes in flow. Additionally, the Kh at the 703-740 FANGVD29 interval is approximately an order of magnitude less than that at the 730-740 FANGVD29 interval, indicating that the aquifer at 703-730 FANGVD29 is less permeable than at 730-740 FANGVD29.

Kh values exceeded 2.0 ft/d in the interval from 727 to 747 FANGVD29 at borehole DF13, even though the flowmeter log failed to detect flow, and, thereby, identify permeable intervals, under ambient-flow conditions because of the low vertical hydraulic gradient within the borehole. Areas of elevated permeability were identified at 702, 732-734, 747, and 759 FANGVD29 during flowmeter logging done in conjunction with pumping. The permeable features identified at 702 and 759 FANGVD29 correspond to areas where the Kh was calculated to be less than 0.50 ft/d. The low Kh calculated for the permeable feature at 759 FANGVD29 can be explained, at least partially, by the atypically long (20 ft) packer-test interval at this depth. Flowmeter measurements typically were collected at intervals of 5 ft or less, whereas slug tests were done at intervals of 10 ft or more. Because it is assumed in the slug-test analysis that the tested part of the aquifer is homogenous, the response of the thick low-permeability matrix is combined with the response of the high-permeability fractures and solution openings, resulting in low-permeability estimates for the entire interval. Flowmeter measurements allow for the characterization of permeable features at numerous discrete points within the aquifer, permitting the assembly of a more detailed permeability profile than is possible with a 10-ft packer assembly.

Kh values from test intervals B, C, E, and F in borehole SPW (at 700-720 and about 730-755 FANGVD29) were 1.0 ft/d or greater (fig. B2). Each of these zones is either in or near permeable intervals identified with the flowmeter logs done in conjunction with pumping from the borehole (table 6). Kh values from test intervals D, F and G in borehole PZ1 (at 703-713 and 723-743 FANGVD29) were greater than 0.90 ft/d. Only the 703-713 FANGVD29 interval in this borehole corresponds to a permeable feature identified with the flowmeter log (table 6).

Specific-Capacity Tests

Borehole DF12 was pumped at 13, 33, and 71 gal/min on three different occasions in an attempt to determine the feasibility of a multiple-well, constant-discharge aquifer test. After pumping the borehole at 71 gal/min for 112 minutes, 0.14 ft of drawdown was measured in borehole DF12 and no drawdown was measured in nearby wells PW3, DF10, or MW39. A multiple-well aquifer test was determined to be infeasible for this borehole, leaving a specific-capacity test the only method available for estimation of hydraulic properties for the aquifer at this borehole. The transmissivity of the aquifer at borehole DF-12 was estimated to be 1.30 X 10^5 ft^2/d. This value is consistent with the results of the slug testing from this borehole.

Borehole PZ3 was pumped at 33 gal/min in an attempt to perform a multiple-well, constant-discharge aquifer test. After pumping borehole PZ3 for 100 minutes, about 22 ft of drawdown was measured the borehole, but no drawdown measured in nearby wells AW1S, AW1D, AW3, SPW, B3, PZ1, and PZ2 (fig. 7). The transmissivity of the aquifer at borehole PZ3 was estimated to be 130 ft^2/d.

Multiple-Well Aquifer Tests

Multiple-well aquifer tests were done in the vicinity of borehole SPW and borehole DF4D (table 3). These test provided substantial insight into the flow pathways within the aquifer.

Borehole SPW

A multiple-well, constant-discharge aquifer test was done in June 1987 by pumping 20 gal/min from borehole SPW over a period of 3,140 minutes. Borehole PZ1 was 115 ft deep when this test was done and boreholes PZ3, AW1S, AW1D, and AW3 had not yet been drilled. The data from this test indicate that the Galena-Platteville aquifer is anisotropic and unconfined in this area and acts as a double-porosity medium (Kay and others, 1989). Drawdown preferentially was oriented N. 60° W. from borehole SPW, parallel to the dominant regional fracture orientation and the orientation of inclined fractures identified in borehole SPW (fig. B5). Aquifer transmissivity was at a maximum of 670 ft^2/d directed N. 60° W. from borehole SPW and at a minimum of 490 ft^2/d perpendicular to the N. 60° W. direction. Kh values ranged from 5.8 to 8.0 ft/d, and the specific yield ranged from 0.017 to 0.148. After initially dropping, water levels in observation wells B3, B5 and PZ2 began to rise about 1,000 minutes into the test and were about 0.10 to 0.60 ft higher at the end of the test (3,140 minutes) than at about 1,000 minutes. Water levels in observation wells PW3, MW8, MW9, PZ1, and B4 dropped during the entire test. The increase in water levels in wells B3, B5, and PZ2 could not be correlated with background water-level fluctuations, indicating that the upper part of the aquifer in the vicinity of wells B3, B5, and PZ2 may have become hydraulically isolated from the fractures supplying water to borehole SPW during the test, presumably due to localized desaturation of the upper fractured zone identified by the cross-hole GPR surveys. Wells B5 and PZ2 are located in zone 1, a part of the aquifer characterized by low permeability, especially in the upper part of the aquifer and low vertical hydraulic interconnection. Well B3 is located in a part of the aquifer that appears to be in poor hydraulic connection with the rest of the aquifer. It is presumed that the water level did not increase in borehole PZ1 because the part of the aquifer monitored by borehole PZ1 remained hydraulically connected to borehole SPW by flow through vertical fractures connected to the lower fractured zone (figs. A5, A6).

Borehole DF4D

A multiple-well, constant-discharge aquifer test was done in February 1992 by pumping 8 gal/min from borehole DF4D for 1,440 minutes. Borehole DF4D was open to the entire thickness of the Galena-Platteville aquifer during the test. Observation wells DF5D, DF6, DF13, and DF14D were screened in the most permeable parts of the aquifer identified from the slug testing and the flowmeter logging.

The data from this test indicate that the Galena-Platteville aquifer is heterogeneous and anisotropic in this area. Drawdown preferentially was oriented N 90° E from borehole DF4D, parallel to the orientation of inclined fractures identified with the televiewer logs in boreholes DF4D and DF5D and roughly parallel to the orientation of the West Ravine in this area (fig. A9). Drawdown also was greater in the middle of the aquifer than at the water table (fig. A9), indicating that the zone of elevated permeability between 730 and 760 FANGVD29 identified with the slug testing and flowmeter logging is the primary pathway for horizontal ground-water flow (Kay and others, 1997)(table 6). A large amount of drawdown was measured at the bottom of the Galena-Platteville aquifer at well MW36, indicating the presence of hydraulically connected secondary-permeability features, most likely inclined fractures, in the lower part of the aquifer in this area. Measurable drawdown in the shallow part of the Galena-Platteville aquifer at well PC3B indicates that the aquifer has some vertical hydraulic connection in upper part of the aquifer in this area, possibly because of the presence of inclined fractures. The absence of drawdown in the shallow part of the Galena-Platteville aquifer at well DF5S indicates that there are few, if any, permeable inclined fractures in the upper part of the aquifer in this area. These results are consistent with the interpretations made from the water-level data that indicated high vertical hydraulic gradients in the aquifer near wells DF4S/4D and DF5S/5D, and lower gradients at wells PC3B/DF6 (tables 4, B2).

Transmissivity values calculated from the constant-discharge aquifer-test data for wells MW36 and DF6D, located along or nearest the direction of maximum drawdown in the aquifer, were about 90 ft^2/d. These values are approximately an order of magnitude lower than transmissivity values of about 725 ft^2/d calculated for wells DF5D and DF13 located furthest from the direction of maximum drawdown in the aquifer. The specific-yield values indicated no clear spatial patterns. The distribution of transmissivity values is contrary to what would be expected for an anisotropic aquifer, where the wells closest to the direction of maximum drawdown have the highest transmissivity, whereas the wells closest to the direction of minimum drawdown have the lowest transmissivity. No curve match could be made for the data from wells DF4S and PC3B. Attempts to calculate a transmissivity tensor using the Papadopulos (1965) method and the method of Hsieh and others (1985) yielded a negative value, indicating that the aquifer is heterogeneous in this area. Aquifer heterogeneity in the vicinity of well DF4D is consistent with the interpretations about aquifer heterogeneity in this area resulting from the analysis of the water-level data. The water-level data indicate borehole DF4D is located in zone 1 but also near transitional areas and zone 2.

Tracer Testing

A constant-discharge aquifer test was conducted as part of a tracer test done in borehole SPW in June and July 1993 (Kay and others, 1999). The tracer test was done to characterize the hydraulic properties of the aquifer in the vicinity of borehole SPW, with specific emphasis on the lower flow pathway identified with the cross-borehole tomography, slug testing, and flowmeter logging done in this area.

Hydrologic conditions for data collection differed between the 1987 and 1993 tests in borehole SPW. Boreholes PZ3, AW1S, AW1D, and AW3 were not present in 1987, but were available for the 1993 test (fig. 7). Borehole PZ1 had been deepened from 115 to 167 ft for the 1993 test. Packers were installed in boreholes PZ1 and PZ3 to provide a more detailed depiction of aquifer response. As a result of abnormally high amounts of precipitation immediately prior to the tracer test, the saturated thickness of the aquifer was about 16 ft higher during the 1993 tracer test than during the 1987 aquifer test.

Borehole SPW was pumped at a constant rate of 20 gal/min for 3,068 minutes while monitoring water levels in observation wells (wells expected to have detectable drawdown) and background wells (wells not expected to respond to pumping stresses). This pumping rate was selected to duplicate conditions during the 1987 aquifer test. The discharge rate was increased to 28 gal/min after 3,068 minutes of pumping and gradually decreased

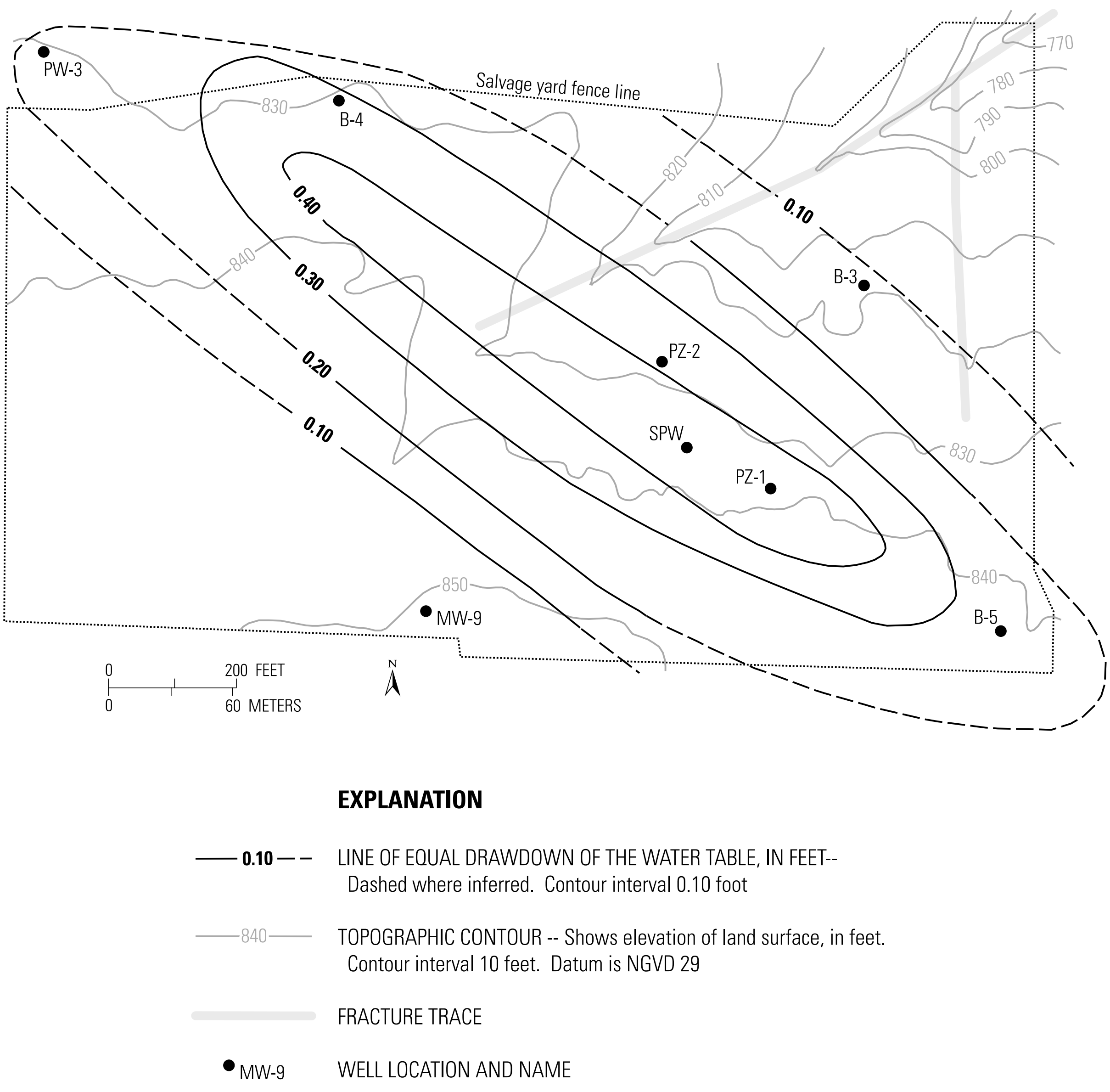

Figure B5. Drawdown of the water table after pumping borehole SPW for 1,000 minutes, Byron site, Ill., June 1987.

to about 25 gal/min by 4,365 minutes. Pumping from borehole SPW stopped after 4,365 minutes. The tracer-injection phase of the test began 150 minutes after the initiation of pumping from borehole SPW when 7.5 gal of tracer water with a concentration of about 20,000 mg/L of bromide was injected into the packed interval in borehole PZ1 (PZ1P) open to the aquifer from 708 to 718 FANGVD29.

Background declines in water levels caused by fluctuations in barometric pressure and recovery from the abnormally high water levels present in the aquifer were more than 2 ft in most of the wells during the tracer test. These background declines in water level were so high that drawdown could not be reliably quantified in the observation wells. Therefore, transmissivity and storativity values were not calculated. The data were analyzed qualitatively to obtain a general understanding of the flow pathways in the vicinity of the tracer test.

Comparison of the trends in water levels with pumping changes clearly indicate that drawdown was observed in boreholes PZ2 and AW1D, and in the packed intervals in boreholes PZ1 and PZ3. These boreholes are close to the pumped borehole and the timing and magnitude of drawdown in these boreholes could be separated easily from background fluctuations for short time periods. Drawdown may have been observed in wells DF21, PW3, B4, AW5D, and AW6, however, the water-level changes were difficult to pick out from the background water-level declines and amount of drawdown, if present, could not be accurately determined at these boreholes over even short time spans. Drawdown was not indicated in the remaining wells, including wells (MW8, MW9, B3) that contained measurable drawdown during the 1987 aquifer test.

Flowmeter and borehole-radar data indicate that water flows to the inclined fracture at borehole SPW primarily through the upper flow pathway around 750 FANGVD29 and the lower flow pathway at about 711 FANGVD29. Because most of the flow is through these pathways, it can be assumed that wells in good hydraulic connection with these pathways will have the largest drawdown, whereas observation wells in poor hydraulic connection with these pathways will have the smallest drawdown. More than 0.90 ft of drawdown was measured at intervals PZ1A (1.35 ft), PZ1P (0.95 ft), and PZ3A (1.15 ft) 100 minutes after the start of pumping. All of these intervals are in good hydraulic connection with the flow pathways supplying water to in borehole SPW. Intervals PZ3P (0.07 ft), PZ3B (0.10 ft), PZ1B (0.32 ft), and wells AW1D (0.08 ft) and PZ2 (0.06 ft) appear to be have moderate hydraulic connection with the flow pathways. Drawdown may have resulted 100 minutes after the start of pumping at wells DF21, PW3 (0.05 ft), and AW5D (0.07 ft). The aquifer in the vicinity of these wells may be hydraulically connected to the flow pathways supplying water to borehole SPW. The absence of detectable drawdown in wells B5 and AW1S, located in the upper part of the aquifer clustered with deeper wells (AW5D and AW1D) that may have had measurable drawdown, indicates that the upper part of the aquifer is not in hydraulic connection with borehole SPW in these areas.

The maximum amount of drawdown measured in boreholes PZ1 (1.35 ft) and PZ3 (1.15 ft) 100 minutes after the start of pumping was above the packed interval, which monitored the upper flow pathway. Drawdown in the test intervals in borehole PZ1 was greater than in the test intervals in borehole PZ3. Because borehole PZ3 is about 10 ft closer to the pumped borehole than borehole PZ1, the larger drawdown in borehole PZ1 indicates that flow is preferential along the orientation of the inclined fractures (N. 60° W.) from borehole SPW to borehole PZ1.

Measurable drawdown in the various packed intervals in borehole PZ3 100 minutes after the start of pumping in borehole SPW during the tracer test contrasts with the absence of hydraulic connection identified at borehole SPW 100 minutes after the start of pumping in borehole PZ3 during the flowmeter logging. The dissimilarity in the response to pumping in this borehole pair, although borehole PZ3 was pumped at a substantially greater rate (33 gal/min as opposed to 20 gal/min), indicates that boreholes PZ3 and SPW are supplied, at least in part, by different secondary-permeability features. The presence of separate permeable features supplying water to boreholes in different parts of the Byron site indicates that the Galena-Platteville aquifer is heterogeneous. The most likely pathway for flow to borehole PZ3 that does not appear to contribute substantial flow to borehole SPW is the vertical fracture between boreholes AW3 and PZ1 outlined by the fracture trace shown in figure 8. However, boreholes AW3 and PZ1 did not clearly show hydraulic connection to borehole PZ3 when it was pumped, so the importance of this fracture on flow cannot be determined.

Monitoring of the concentration of bromide ion with time in the water pumped from borehole SPW (fig. A10) indicated the velocity of the tracer through the lower flow pathway between boreholes PZ1 and SPW under the hydraulic gradient imposed by the pumping was about 152 ft/d. Solution of the Darcy velocity equation results in a calculated effective porosity for the lower flow pathway from 2.6 to 3.5 percent. Combining the effective porosity determined from the tracer test with the water-level and Kh data obtained by use of the packer assembly, solution of the Darcy equation (4) yielded an average ground-water velocity through the lower flow pathway of about 15.4 ft/d under hydrostatic conditions.

The effective porosity of the lower flow pathway is lower than the median primary porosity of the Galena-Platteville deposits of about 10 percent (fig. 11) and exceeds typical effective porosity values for fractures of less than 1 percent. An effective porosity value for the lower flow pathway that is higher than those typical of fractures and lower than those typical of the aquifer matrix indicates that the fractures and matrix in the Galena-Platteville aquifer in this area are connected hydraulically. Hydraulic connection between fractures and matrix is expected for a double-porosity medium such as the Galena-Platteville aquifer.

Location of Contaminants

The concentration and distribution of cyanide and VOC's in the ground water beneath the Byron site was determined by sampling in test intervals isolated with a packer assembly and from completed monitoring wells. As these compounds are not present in nature, their distribution was used as a tracer to define migration pathways through the Galena-Platteville aquifer.

Concentrations of VOC's in the test intervals isolated with a packer assembly in boreholes DF4D (fig. B1), DF5D, DF12 (fig. B3), DF13, and DF17 tended to be higher in the more permeable parts of the aquifer than in the less permeable parts of the aquifer. These patterns indicate preferential flow through the secondary-permeability features in the aquifer and smaller amounts of flow through the less permeable parts of the aquifer.

The distribution of VOCs and cyanide in monitoring wells at the Byron site shows two general areas of VOC's, one at the BSY and downgradient, and another derived from two areas on the DFP (fig. 15). The types of contaminants were variable spatially within the aquifer, making their distribution useful for tracking the movement of water in different parts of the aquifer.

The plume emanating from the BSY is composed primarily of trichloroethene, which migrates northwest to the Rock River along the direction of ground-water flow in this area, and also along the dominant vertical fracture orientation in the dolomite. The plume emanating from the BSY also contains cyanide; however, cyanide largely is confined to the fracture traces in the eastern part of the BSY and Woodland Creek, as well as at Meyer's Spring (fig. 15). Woodland Creek appears to define the extent of contamination in the northeastern part of the Byron site, and appears to be a ground-water sink.

The presence of VOC's in water at monitoring well AW5I in the southeast corner of the BSY upgradient of the source areas is difficult to explain (U.S. Environmental Protection Agency, 1994)(fig. 7). Well AW5I is open to the middle of the Galena-Platteville aquifer immediately above the shaley layer near the top of the Grand Detour Formation, and the well is hydraulically upgradient of disposal areas on the BSY. Wells B5, open to the water table, and AW5D, open to the base of the Galena-Platteville aquifer, are clustered with well AW5I, and do not contain VOC's. The presence of contaminant in the middle of the aquifer hydraulically upgradient of the defined disposal areas indicates one of two possibilities. There may be components of flow in the aquifer opposite to the northerly direction of flow indicated by the water-level data. Alternatively, contaminants (presumably in the form of a dense nonaqueous phase liquid) may have migrated at depth from the disposal areas to the area of well AW5I, presumably along the top of the shaley layer at the top of the Grand Detour Formation. The shale layer dips to the south in this area (fig. 10).

Two plumes are present in separate areas on the southern part of the DFP (fig. 15). The first is composed primarily of trichloroethene (TCE) and trichloroethane (TCA). The second is composed of TCA and chloroform. Both plumes migrate southwest to the Rock River along the West Ravine and approximately along the direction of the secondary vertical fracture orientation identified in the dolomite. Although water-level and water-quality data are not available in much of the area south of the DFP water-level data indicate that flow is from the area south of the DFP is northward toward the West Ravine. The presence of VOC's in the Galena-Platteville aquifer south of the DFP indicates flow opposite to the direction indicated by the water-level data.

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